



Sanionia uncinata and *Salix polaris* as bioindicators of trace element pollution in the High Arctic: a case study at Longyearbyen, Spitsbergen, Norway

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Received: 27 August 2018 / Revised: 27 May 2019 / Accepted: 8 June 2019 / Published online: 19 June 2019
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Abstract

Longyearbyen (Spitsbergen) is influenced by local contamination sources, such as exhausts from power plants, traffic, coal mines, and industrial waste dumps subject to weathering, which threatens soil and living organisms. Therefore, the trace element level in this area needs to be evaluated. The moss *Sanionia uncinata* and prostrate dwarf-shrub *Salix polaris* were collected as contamination indicators. Concentrations of Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, and Zn in these species were measured. The tested hypotheses were: in Longyearbyen and its vicinity (1) the moss *S. uncinata* and the willow *S. polaris* may be used as phytoaccumulators and therefore as bioindicators and bioremediators of certain trace elements; (2) the moss *S. uncinata* contains higher concentrations of metals than the willow *S. polaris*. The soil of Longyearbyen was contaminated with Cd, Co, Cu, Ni, Pb, and Zn. The willow *S. polaris* may be used in phytoaccumulation and therefore in the bioremediation and bioindication of Cd and Zn from its environment. Stems of *S. polaris* from Longyearbyen are better bioindicators of Cr, Cu, Hg, Ni, and Pb and poorer bioindicators of Cd, Mn, and Zn than leaves of this species. *S. polaris* (both stems and leaves) was a better bioindicator of Cd and Zn concentrations than green gametophytes of *S. uncinata*. *S. uncinata* was a better bioindicator of Co, Cr, Cu, Fe, Hg, Mn, Ni, and Pb than *S. polaris*.

Keywords Moss · Arctic tundra · Coal mine · Bioaccumulation factor · Transfer factor

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s00300-019-02517-0>) contains supplementary material, which is available to authorized users.

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Introduction

Longyearbyen is the largest town in Spitsbergen, the largest island of the Svalbard archipelago, with about 2200 inhabitants and additionally with tourists visiting this area (Reimann et al. 2009). Longyearbyen is located in the Arctic, an area recognized as low polluted, but with a certain number

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of contamination sources (Johansen and Tømmervik 2014). These are a coal and diesel fuel power plant and transportation, e.g., snowmobiles, passenger cars, and heavy duty vehicles (Reimann et al. 2009; Aamaas et al. 2011). Coal mining in the Longyearbyen area started in 1906 and seven mines were established. Since 1961 the mines had been consecutively shut down up to 1996. Nowadays only one, Gruve 7, is active (Piepjohn et al. 2012). Although other coal mines are no longer active, the remains of the mines and heaps of industrial waste accumulated for decades still exist. They are subjected to weathering (especially thawing) and leaching of acid solutions (acid mine drainage) with metals being a threat to soil and living organisms (Holm et al. 2003; Elberling et al. 2007; Askaer et al. 2008; García-Moyano et al. 2015). In addition, airborne sediments of coal particles may be a source of pollution over broad areas (Holte et al. 1996). As well as local contamination also long-range transport from lower latitudes may supply agents, such as metals, to Spitsbergen (Rose et al. 2004; Samecka-Cymerman et al. 2011; Kozak et al. 2015). This area is considered heavily affected by specific atmospheric circulation patterns bringing various xenobiotics from Europe's industrialized areas, especially in winter (Birks et al. 2004). According to Kłos et al. (2017) also sea aerosol is a source of anthropogenic Cs-137, Pb-210, Th-231, Pb, and Hg which affect the soil and biota near Longyearbyen. The same authors proved elevated levels of Ni in moss, lichen, and vascular plant samples (*Salix polaris* Wahlenb. and *Cassiope tetragona* L.D.Don.) as a result of factors, such as coal mining around Longyearbyen (Kłos et al. 2017). The biotas in Svalbard are very sensitive to any harmful human influence because of low productivity and a small number of species (Poikolainen et al. 2004). Xenobiotics accumulate and biomagnify at each trophic level and even small amounts influence considerable parts of the ecosystems (Gulińska et al. 2003; Birks et al. 2004; Wilkie and La Farge 2011). Therefore, examination of metal levels in the Arctic environment is very important for the safety of these special ecosystems (Askaer et al. 2008; Kozak et al. 2015; Halbach et al. 2017). These elements are particularly dangerous being non-degradable and they may be distributed throughout the ecosystem for many years once discharged into the environment (Kabata-Pendias 2011). Mosses are one of the most widespread plants with respect to phytomass productivity, and they have a crucial role in the function of polar terrestrial ecosystems (Smith 1982; Douma et al. 2007; Gornall et al. 2007; Longton 2008). According to Douma et al. (2007) especially their role of a discriminatory blanket for nutrient speciation is very important. These plants are able to continue growth at low temperatures in areas where the growing season is short. Additionally, they stabilize soil and release elements from rocks so their decomposed litter contributes to pedogenesis and nutrient cycling. After glacier retreat mosses are

important pioneers for primary succession. Some of them are able to fix atmospheric nitrogen thanks to cooperation with cyanobacteria (Martin and Mallik 2017). Mosses accumulate elevated levels of xenobiotics, and therefore, since 1968 (Rühling and Tyler 1968), they have been commonly used as ecological indicators all over Europe (Kosior et al. 2010; Kłos et al. 2015). These plants have a high surface-to-volume ratio and immense exchange capacities for cations due to the absence of a well-developed cuticle, which simplifies their accumulation of trace elements (Gerdol et al. 2000; Zechmeister et al. 2003).

The aim of this study was to investigate the level of Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, and Zn in the representative Arctic moss *Sanionia uncinata* (Hedw.) Loeske and for comparison in the willow *S. polaris* collected in Longyearbyen and its vicinity. *S. uncinata* has already been used as an ecological indicator of pollution in Spitsbergen and Antarctica (Grodzińska and Godzik 1991; Yogui and Seicano 2008; Samecka-Cymerman et al. 2011; Kłos et al. 2015, 2017). Furthermore, *S. polaris* was reported by Wojtuń et al. (2013) as a bioindicator of metals in the Svalbard environment. The tested hypotheses were: in Longyearbyen and vicinity: (1) moss *S. uncinata* and the willow *S. polaris* may be used as phytoaccumulators and therefore as bioindicators and bioremediators of certain trace elements; (2) *S. uncinata* contains higher concentrations of metals than *S. polaris*.

Materials and methods

Sampling design

The study site, Longyearbyen (78°13'N, 15°38'E), and the vicinity were investigated in July 2016. Fifty-two sites (numbered 1–52) were selected within the city and 15 sites (Nos 53–67) in the neighboring mining areas (Fig. 1). The following sampling sites were situated on slopes: sites 53 and 54 on the abandoned Nye Gruve I mine; sites 62–64 on an abandoned mine without an established name; and sites 57–59 and 61 on the abandoned Nye Gruve II mine. Thus, these sites were at a particular risk of runoff from coal waste. The investigated area was divided into 30 m × 30 m² of which sampling squares were selected by random sampling (each possible square was numbered and then three of them were drawn by a random number generator). In each sampling square gametophytes (green parts) of *S. uncinata* and above-ground parts of *S. polaris* were collected from 10 m × 10 m² in three replicates. Each plant sample comprised a mixture of three subsamples. Because the goal of this study was to evaluate the ability of both species to reflect trace element deposition, plant samples were not washed (Čeburnis and Steinnes 2000). Also Kozlov et al. (2000) and Oliva and Valdés

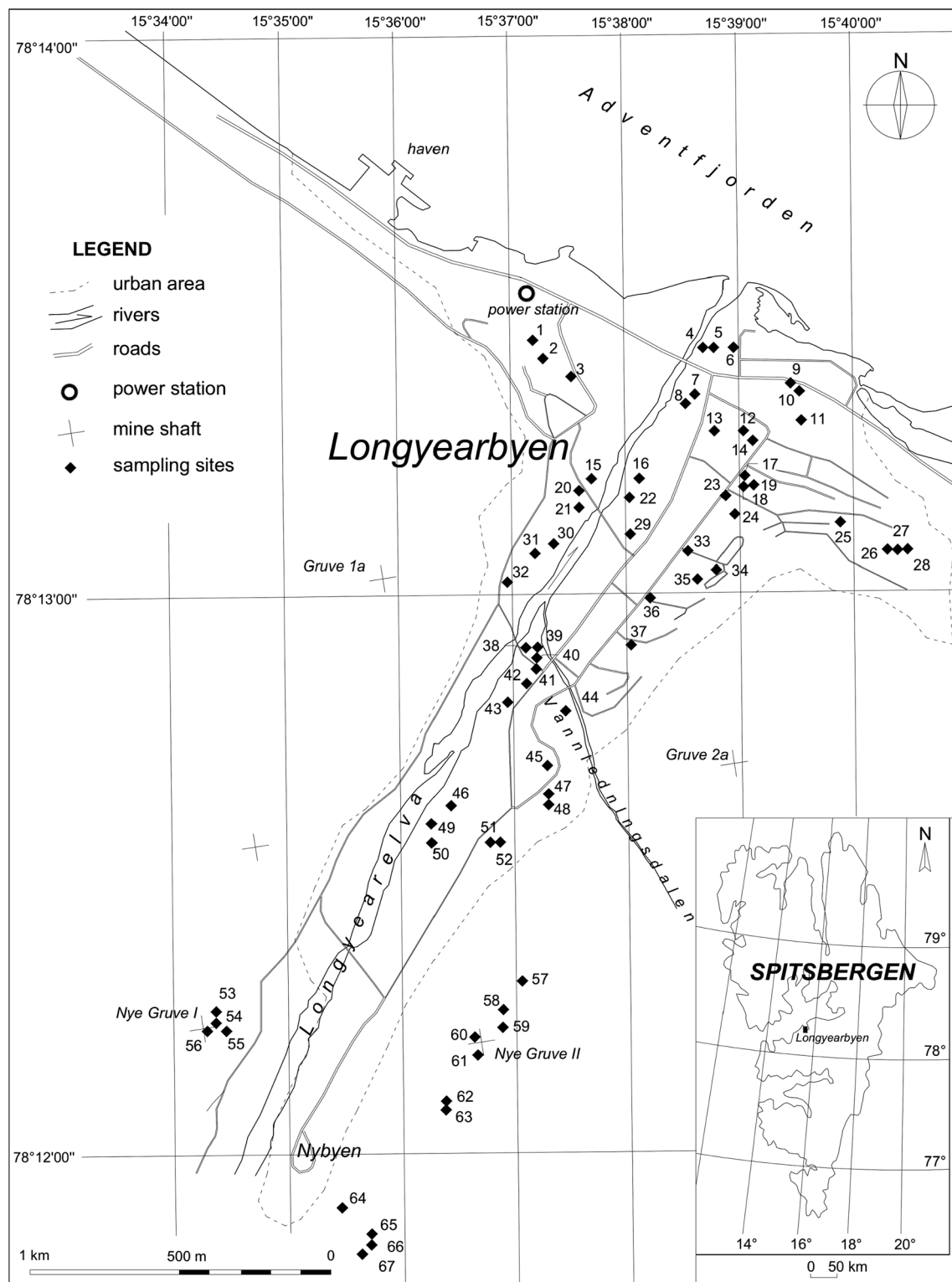


Fig. 1 Location of the sampling sites

(2004) recommend that leaf samples should not be washed for bioindication processes in industrially polluted sites. Litter, dead material, and soil particles were manually

removed from the moss and the willow. Additionally, topsoil samples (about 1 kg in weight) from a depth of 0–10 cm were collected using a plastic hand shovel and

plastic bags from the *S. uncinata* and *S. polaris* collection sites, in five replicates from each square. Stones and plant remains were removed from the soil. The number of collected samples was based on preliminary determination to obtain reliable analytical results. All of the investigated topsoil layers were mineral layers with an average total organic carbon (TOC) content of 6.91%. TOC content in the topsoil layers ranged from 1.38 to 36.36%. It should be noted that the highest TOC contents were always related to the high content of fine coal fragments in the topsoil layer, and they were not related to the organic character of the soil. Most of the investigated topsoil layers exhibited sandy loam or silt loam texture. In some cases, loamy or loamy fine sand texture was present. Most of the investigated topsoil layers were characterized by a high content of SiO_2 , Al_2O_3 , and Fe_2O_3 as well as a low content of K_2O , Na_2O , CaO , MgO , and P_2O_5 . The most common minerals in the investigated topsoil layers were quartz, K-feldspar, plagioclase, mica, and chlorite.

Soil and plant analysis

The willow *Salix polaris* was divided into leaves and stems. Soil and plant samples were dried at 50 °C to constant weight. This temperature was low enough to prevent mercury loss (Lodenius et al. 2003). A preliminary experiment proved that mercury did not evaporate at this temperature. Soil samples were sifted through a Morek Multiserw LPzE-2e 2 mm sieve shaker and then homogenized with a Fritsch Pulverisette 2 mortar grinder. 300 mg of dry weight (in triplicate) of soil and plant samples was digested with 3 mL of ultra-pure (65%) nitric acid and 2 mL of ultra-pure (70%) perchloric acid in a microwave oven (CEM Mars 5). The digests were diluted to 50 mL with deionized water. In these soil and plant digests, Fe, Mn, and Zn concentrations were analyzed using FAAS (Avanta PM from GBC) and Cd, Co, Cr, Cu, Ni, and Pb using GFAAS (PinAAcle 900Z from Perkin-Elmer). The elements were controlled against Atomic Absorption Standard Solutions from Sigma Chemical Co. and blanks which contained the same matrix as the samples and were processed as samples. Mercury was detected directly in powdered solid and plant samples using an AMA 254 Advanced Mercury Analyser. Results of metal concentrations for soil and plants were calculated on a dry weight basis. The accuracy of the methods employed for the evaluation of metal concentrations in soil and plant samples was controlled against Certified Reference Materials: moss M2 and M3 (Finnish Forest Research Institute) and Steinnes et al. (1997), and Chestnut Soil, Bainaimao and Bayan Obo, Neil Mongol in China GBW07402 (GSS-2). Coefficients of variance (CV) established for the measured

metal concentrations in the reference materials are listed as Online Resources 1 and 2.

Statistical analysis

One-way ANOVA, combined with Tuckey's post-hoc test, was used to test for the statistical significance of differences between 67 sites in metal concentrations in soil, and moss *S. uncinata* and the willow *S. polaris* stems and leaves. *T* tests were employed to analyze the differences between two groups of pooled samples: leaves versus mosses and leaves versus stems. Pearson correlations were calculated between trace element concentrations in soil and *S. polaris* stems and leaves. Data were log-transformed to obtain normal distribution (Zar 1999). Shapiro–Wilk's *W* test was used for normality control and the Brown-Forsythe test for the evaluation of the homogeneity of variances (Brown and Forsythe 1974; Argaç 2004).

The concentrations of Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, and Zn in *S. uncinata* and *S. polaris* leaves from 67 sites were ordered to reveal possible gradients of metal levels through principal component and classification analysis (PCCA). Plots of PCCA ordination of *S. uncinata* and *S. polaris* leaves and projection of the metal concentrations on the factor plane provide information about similarities between samples and show relations between the original variables and the first two factors (Legendre and Legendre 1998). Subsequently, samples were divided into a city group including 52 sites (1–52) and into a mine group including 15 sites (53–67) in the neighboring mining areas (Fig. 1). PCCA analysis was performed for the concentrations of Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, and Zn in *S. uncinata* from the city group. Mn was excluded as a supplementary variable having the lowest correlation with factor 1 and 2. An exceptional feature of PCCA is the possibility to determine active and supplementary variables. The active variables are applied to derive principal components. The supplementary variables can be projected onto the factor space calculated from the active cases and variables. Therefore, conclusions may be made concerning these variables, even though the supplementary variables are not included in the analysis (Zuur et al. 2007). Another PCCA for *S. uncinata* from 15 mining group sites was performed for the concentrations of Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, and Zn.

The bioaccumulation factor (BF) is an important tool for the evaluation of the phytoremediation potential of a species. When higher than one, it indicates the ability of a plant to accumulate trace elements from soil and transport them to aerial parts (Galal and Shehata 2015). Thus, the Stem Bioaccumulation Factor, SBF (stems-to-soil ratio), Leaves Bioaccumulation Factor, LBF (leaves-to-soil ratio), and stem to leaves transfer factor, TF (leaves-to-stems ratio), were calculated for concentrations of metals in the willow *S. polaris*.

For the statistical calculations Dell Inc. software version 13 (2015) was used.

The spatial distribution of metals in *S. uncinata* in the study area was estimated by ordinary kriging using an exponential variogram model (Walter et al. 2001). The sample size (neighborhood search) was set globally, and all 67 data points were used to interpolate each trace variable into a regular 10 m resolution grid. The predicted surfaces were, respectively, classified using defined interspacing with the geometric intervals method of classification (Martín et al. 2007; Zamani-Ahmadmamdoodi et al. 2014). Geostatistical analysis was carried out using Geostatistical Analyst extension for ArcGIS for Desktop 10.2.2 (ESRI 2016).

Results

The soils and plants differed significantly between the sites with regard to the concentrations of the metals assessed for soil (all $p < 0.001$): Cd ($F_{66,268} = 3.4$), Co ($F_{66,268} = 2.6$), Cr ($F_{66,268} = 3.4$), Cu ($F_{66,268} = 3.5$), Fe ($F_{66,268} = 3.1$), Hg ($F_{66,268} = 5.3$), Mn ($F_{66,268} = 3.4$), Ni ($F_{66,268} = 2.8$), Pb ($F_{66,268} = 2.9$), Zn ($F_{66,268} = 3.7$). *S. uncinata* Cd ($F_{66,134} = 4.8$), Co ($F_{66,134} = 3.5$), Cr ($F_{66,134} = 2.6$), Cu ($F_{66,134} = 3.7$), Fe ($F_{66,134} = 3.1$), Hg ($F_{66,134} = 4.5$), Mn ($F_{66,134} = 5.3$), Ni ($F_{66,134} = 2.5$), Pb ($F_{66,134} = 4.9$), Zn ($F_{66,134} = 4.1$). *S. polaris* stems Cd ($F_{66,134} = 5.8$), Co ($F_{66,134} = 20.4$), Cr ($F_{66,134} = 28.1$), Cu ($F_{66,134} = 23.5$), Fe ($F_{66,134} = 12.8$), Hg ($F_{66,134} = 8.9$), Mn ($F_{66,134} = 11.3$), Ni ($F_{66,134} = 6.1$), Pb ($F_{66,134} = 15.1$), Zn ($F_{66,134} = 15.9$) and leaves Cd ($F_{66,134} = 13.8$), Co ($F_{66,134} = 17.3$), Cr ($F_{66,134} = 13.9$), Cu ($F_{66,134} = 11.7$), Fe ($F_{66,134} = 27.4$), Hg ($F_{66,134} = 9.1$), Mn ($F_{66,134} = 13.1$), Ni ($F_{66,134} = 9.3$), Pb ($F_{66,134} = 10.1$), Zn ($F_{66,134} = 21.9$). The concentrations of

elements in soils were higher than those reported by Wojtuń et al. (2013) for Cd, Cu, Fe, Mn, Pb, Zn collected in Svalbard within up to a 3-km radius of the Polish Polar Station (77°00'N; 15°33'E) (Table 1). Maximum Cd, Co, Cu, Ni, Pb, and Zn concentrations were even higher than the admissible limits for soils in Poland (MŚ 2002), while those of Cr, Cu, Ni, Pb, and Zn were higher than the background values in Norwegian soils (Vik et al. 1999) (Table 1). The maximum concentration of Hg was higher than the average of unpolluted soil ($< 0.2 \text{ mg kg}^{-1}$) Martín and Nanos (2016). Maximum concentrations of Cd, Co, Cr, Cu, Mn, Ni, and Zn in *S. uncinata* in this investigation (Table 2) were higher than those in the same species investigated in the southern part of Spitsbergen on Wedel Jarlsberg Land (Table 3) by Samecka-Cymerman et al. (2011) and Wojtuń et al. (2013). Comparable concentrations of Fe and Hg and lower concentration of Pb (Table 3) in *S. uncinata* in this investigation in comparison with *S. uncinata* reported by Samecka-Cymerman et al. (2011) and Wojtuń et al. (2013) were established. These concentrations in *S. uncinata* from Longyearbyen were also higher than in the same species from the Bellsund area reported as mean values (Table 3) investigated in 1987–1995 (Jóźwik 2000). Metal concentrations in stems and leaves of *S. polaris* in this investigation were also higher than in *S. polaris* examined by Wojtuń et al. (2013) in the less polluted southern part of Spitsbergen in the vicinity of the Polish Polar Station (Table 3). The maximum concentration of Cd in the willow *S. polaris* leaves and of Zn in *S. polaris* stems and leaves exceeded the toxicity threshold (mg kg^{-1}) of > 5 and > 100 , respectively, for the protection of food chains in ecosystems (Kabata-Pendias 2011). In addition, Bioaccumulation Factors (BFs, Table 4) calculated for *S. polaris* from soil to stems (SBF) and from soil to leaves (LBF) were the highest for Cd and Zn (higher than one)

Table 1 Minimum, maximum, median, and median average deviation (MAD) of the concentration (mg kg^{-1} dry weight) of metals in the soils of the investigated area ($n = 335$)

	Soil				References		
	Minimum	Maximum	Median	MAD	W	Ps	Ns
pH _{H2O}	3.8	7.8	5.8	0.5			
Cd	0.02	1.7	0.2	0.05	0.05–0.4	1	0.1–1.7
Co	1.1	35	13	2.3	13–60	20	
Cr	5.2	42	30	3.3	16–47	50	3–30
Cu	2.2	111	30	6.1	17–92	30	6–27
Fe	7960	35,800	25,400	2277	16,300–90,546		
Hg	0.02	0.5	0.05	0.02		0.5	0.05–0.20
Mn	24	808	365	84	242–1600		
Ni	2.9	52	27	5	12–78	35	3–19
Pb	2.0	141	19	3	9–38	50	8.5–107
Zn	21	436	79	12	52–345	100	25–104

In the column of references: W elements (mg kg^{-1}) in Svalbard soils reported by Wojtuń et al. (2013); Ps admissible limits for Polish agricultural soils (MŚ 2002), Ns background value in Norwegian soils by Vik et al. (1999)

Table 2 Minimum, maximum, median, and median average deviation (MAD) of the concentration (mg kg⁻¹ dry weight) of metals in *Sanionia uncinata* and *Salix polaris* stems and leaves ($n = 201$); significance level (p) for the t test for comparison of *S. uncinata* (S) and *S. polaris* stems (SSs), *S. uncinata* and *S. polaris* leaves (SSI) as well as *S. polaris* stems and *S. polaris* leaves (SSSI)

	<i>S. uncinata</i>				<i>S. polaris</i> stems				<i>S. polaris</i> leaves				SSs		SSI		SSSI	
	Minimum	Maximum	Median	MAD	Minimum	Maximum	Median	MAD	Minimum	Maximum	Median	MAD	p	p	p	p	p	p
Cd	0.1	3	0.3	0.2	0.9	5.0	3.0	0.6	1.1	8.5	3.1	1.2	<0.001	<0.001	<0.001	<0.001	<0.05	<0.001
Co	2.0	54	10	5.0	0.4	4.1	1.1	0.5	0.6	5.9	1.7	0.5	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Cr	7.6	54	14	3.8	1.6	12	4.1	1.8	0.2	8.1	1.4	0.9	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Cu	3.4	55	20	8.0	5.6	24	11	2.3	4.1	16	6.9	1.0	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Fe	4240	13,300	9050	1751	145	2390	980	363	119	6890	897	470	<0.001	<0.001	<0.001	<0.001	>0.05	<0.001
Hg	0.02	0.12	0.04	0.01	0.004	0.024	0.011	0.002	0.002	0.034	0.008	0.003	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Mn	81	2640	206	75	41	362	121	34	82	981	279	97	<0.001	<0.001	>0.05	<0.001	<0.001	<0.001
Ni	8.9	48	24	8.1	4.6	45	16	3.6	2.1	22	8.4	2.5	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Pb	1.5	20	5.9	1.5	0.2	3.1	0.8	0.3	0.2	1.7	0.6	0.2	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Zn	30	261	89	36	161	433	281	36	154	575	361	78	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

compared to the other metals. In addition, the t test revealed that *S. polaris* contained significantly higher concentrations of Cd ($t_{132} = -12.4$, $p < 0.001$) and Zn ($t_{132} = -17.9$, $p < 0.001$) in leaves than green parts of *S. uncinata* gametophytes. The concentration of all the other examined elements was significantly higher in the moss. The same pattern was observed for stems of *S. polaris* (Cd $t_{132} = -15.6$, $p < 0.001$ and Zn $t_{132} = -17.5$, $p < 0.001$) in comparison with green parts of moss gametophytes. T test (all $p < 0.001$) revealed that *S. polaris* leaves contained significantly lower concentrations of Cr ($t_{132} = 12.6$), Cu ($t_{132} = 78.9$), Ni ($t_{132} = 3.2$) and Pb ($t_{132} = 6.7$) than stems. The Translocation factor (TF) for *S. polaris* from stems to leaves was > 1 in the order of Mn $>$ Co $>$ Zn $>$ Cd (Table 4).

Discussion

Elevated metal levels in soils in Longyearbyen may point to the influence of local sources of pollution (Rose et al. 2004; Martín and Nanos 2016). These may be snow with carbon dust from a stockpile and power plant containing Hg in the amount 200-fold higher than the background as this element together with Cu, Zn, Pb, Mn, Cr, Ni, Cd, As are important constituents of coal and coal combustion products (Aamaas et al. 2011; Burmistrz and Kogut 2016; Shang-guan et al. 2016). Elevated metal levels in *S. uncinata* may indicate that in Svalbard, not only local but also long-range airborne transport from lower latitudes may contribute to contamination (Rose et al. 2004; Samecka-Cymerman et al. 2011; Kozak et al. 2015). The highest levels of contaminants from coal combustion in sites near Longyearbyen may demonstrate that even low-level industry can be a significant source of pollution in such a vulnerable area with low deposition (Rose et al. 2004). The higher concentration of Pb in *S. uncinata* from the vicinity of the Polish Polar Station than in *S. uncinata* collected in Longyearbyen may be explained by the fact that this station is heated by oil burning and additionally equipped with a waste incinerator. Unleaded gasoline and diesel fuel contain certain quantities of Pb as crude oil is geogenically contaminated with lead (Kummer et al. 2009). The significantly higher concentrations of Cd and Zn in *S. polaris* leaves and stems than in the green parts of *S. uncinata* gametophytes may indicate that *S. polaris* is a good accumulator of Cd and Zn and a better bioindicator of the concentration of both elements in the environment in comparison with the moss species. Similar results of Cd in concentrations higher than the average values and Zn in concentrations exceeding the physiological needs for *S. polaris* in Longyearbyen and Barentsburg are reported by Jóźwik (2000) and Wojtuń et al. (2013). This resistance to elevated Cd levels may be caused by the apoplasmic detoxification ability of *Salix* sp. for this metal (Harada et al. 2011). *S.*

Table 3 Concentrations of metals (mg kg⁻¹) in *Sanionia uncinata* from Svalbard established by Jóźwik (2000), Samecka-Cymerman et al. (2011), Wojtuń et al. (2013) as well as in stems and leaves of *Salix polaris* from Svalbard established by Wojtuń et al. (2013) and Krajcarová et al. (2016)

Reference	Cd	Co	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn
<i>S. uncinata</i>										
Jóźwik (2000)	0.7			7.6			40		12.4	66
Samecka-Cymerman et al. (2011) and Wojtuń et al. (2013)	0.03–0.98	0.3–16	0.8–22	2.1–29	250–15,900	0.03–0.1	17–850	0.01–17	0.07–32	8.8–132
<i>S. polaris</i> stem and leaves										
Wojtuń et al. (2013)	0.6–2.3	0.4–3.0	0.1–1.5	4–7	130–660	0.01–0.09	140–280	2.6–7.0	0.1–1.2	61–180
<i>S. polaris</i> stem										
Krajcarová et al. (2016)	0.2–5.3	0.2–1.1	<3.6	4.7–35	100–1500	<0.013	20–210	3.9–12	0.3–9.4	100–500
<i>S. polaris</i> leaves										
Krajcarová et al. (2016)	0.6–1.5	0.1–1.5	<3.2	4.5–26	100–1300	<0.013	40–300	1.3–8	<5.4	200–1100

Table 4 Minimum, maximum, and median of the Stem Bioaccumulation Factor (SBF, stem-to-soil ratio), Leaf Bioaccumulation Factor (LBF, leaves-to-soil ratio), Transfer Factor (TF, leaves-to-stems ratio) of metals in *Salix polaris*

	SBF			LBF			TF		
	Minimum	Maximum	Median	Minimum	Maximum	Median	Minimum	Maximum	Median
Cd	0.8	55	15	2.0	60	17	0.6	2.6	1.1
Co	0.03	0.4	0.1	0.04	0.7	0.1	0.8	3.3	1.4
Cr	0.04	0.4	0.2	0.01	0.2	0.05	0.1	1.1	0.4
Cu	0.09	0.8	0.4	0.06	1.1	0.2	0.3	1.7	0.6
Fe	0.01	0.1	0.04	0.01	0.3	0.04	0.2	4.8	1.0
Hg	0.01	0.7	0.2	0.01	0.9	0.1	0.2	1.9	0.8
Mn	0.14	1.3	0.3	0.2	3.6	0.8	1.1	4.4	2.5
Ni	0.2	1.6	0.6	0.07	1.2	0.3	0.2	1.7	0.5
Pb	0.001	0.2	0.04	0.002	0.1	0.02	0.01	0.04	0.01
Zn	0.9	6.2	3.4	1.3	8.6	4.4	0.9	2.2	1.3

polaris leaves contained significantly lower concentrations of Cr, Cu, Hg, Ni, and Pb than stems. This may be explained by the fact that leaves are shed for winter and thus stems may indicate longer-term air pollution effects (Harju et al. 2002). However, atmospheric deposition or soil surface dust is more easily washed out from the leaf surface than from the outer bark surface. On the other hand, some trace elements show higher uptake in tree leaves than deposition, resulting in negative throughfall fluxes (Avila and Rodrigo 2004; Samecka-Cymerman et al. 2011). Furthermore, bark is a better pollution indicator than leaves due to longer exposure time (Reimann et al. 2007). Significantly higher Cd ($t_{266} = -6.4$, $p < 0.001$), Mn ($t_{266} = -10.6$, $p < 0.001$) and Zn ($t_{266} = -25.4$, $p < 0.001$) concentrations in leaves than in stems are in agreement with Vandecasteele et al. (2005) who report that willows translocate Mn and Zn mainly to leaves. These authors also found higher Cd concentrations in leaves than in stems of this species (Vandecasteele et al. 2005). These results indicate that stems of *S. polaris* from Longyearbyen are a better bioindicator of Cr, Cu, Hg, Ni, and Pb and poorer bioindicators of Cd, Mn, and Zn than leaves.

S. polaris Bioaccumulation Factors (SBF and LBF, Table 4) are the highest for Cd and Zn compared to the other metals, which may indicate that both elements were most heavily accumulated by this species. Therefore, *S. polaris* could be used in the bioremediation of Cd and Zn toxicants from the environment, especially that this species accumulated Zn in leaves and stems proportionally to its concentration in soil with positive significant correlation ($p < 0.01$). Kabata-Pendias (2011) considers Cd as a metal which shows preferential accumulation by terrestrial plants with a BF of 10. The maximum values of this factor for Cd were much higher in *S. polaris* in this investigation: 55 in stems and 60 in leaves (Table 4). Kabata-Pendias (2011) shows Zn to undergo medium intensive accumulation in terrestrial plants with a BF of 0.6–0.8. The maximum values of this factor for Zn were also much higher in *S. polaris* from this investigation: 6.2 and 8.6 (Table 4). Unfortunately there are no data presenting Bioaccumulation Factors for Zn in the willow *S. polaris* from Arctic areas. *Polygonum thunbergii* from the industrial area of Korea (Kim et al. 2003) exhibits a higher BF for Zn: 28 as compared to *S. polaris*. The Translocation

Factor (TF) from *S. polaris* was the highest for Mn, which indicates internal element transport where Mn seems to be the most effectively transported element from shoots to leaves. This is in agreement with Olivares et al. (2009) that Mn as an essential nutrient is actively transported to photosynthetic tissues. The lowest TF for Pb in *S. polaris* (Table 3) was probably caused by the fact that Pb as a toxic and non-essential metal exhibits low translocation within plants (Sultan 2000; Sharma and Dubey 2005).

PCCA ordination calculated for metal concentrations in moss *S. uncinata* and leaves of the willow *S. polaris* from 67 sites is presented in Fig. 2. The 1st principal component discriminates between polar willows (positive scores) and mosses (negative scores). The 2nd component is related (negative scores) to *S. uncinata* in site 10. Projection of the variables on the factor plane (Fig. 2) indicates that *S. polaris* was correlated with the highest concentrations of Cd and Zn in its tissues. *Sanionia uncinata* was correlated with the highest concentrations of Co, Cr, Cu, Fe, Hg, Ni, and Pb in its tissues. *Sanionia uncinata* from site 10 was correlated with the highest concentration of Mn. This site was situated within heath vegetation but in a close vicinity of wetland vegetation occupied by birds, mostly those feeding at sea. The highest amounts of Mn (compared to other metals) are transported by contaminated rivers to seas and oceans (Kabata-Pendias 2011). Seabirds are a crucial factor influencing the concentration of elements in the arctic

soils (Ziółek et al. 2017). Birds which forage in the ocean accumulate metals, released via droppings on land and thus concentrating pollution to amounts that can be significant in the coastal ecosystem (Liu et al. 2006). Ziółek et al. (2017) found increased concentrations of Mn as well as Cu, Cd, and Zn in soils influenced by seabird colonies. In addition, Samecka-Cymerman et al. (2011) report the highest concentration of Mn in *S. uncinata* from sites closest to the shoreline and thus most influenced by sea spray as well as from sites influenced by birds. Because of their high position in the nutritional chain, seabirds concentrate high levels of trace elements in their tissues (Lucia et al. 2016).

Ordination by PCCA calculated for 52 sites (Nos 1–52) of *S. uncinata* from Longyearbyen (Online Resource 3) shows that the first principal component discriminates mosses from sampling sites situated in the vicinity of streets, and vehicle and snowmobile parking places, e.g., 6, 9–11, 17–19, 29 (negative scores). *Sanionia uncinata* from sites closest to the power plant (sites 1–3) and in the vicinity of an abandoned station of the conveyor for coal transportation (sites 15, 20–21), all growing in soil covered with coal dust, show positive scores of the second principal component. Projection of the variables on the factor plane indicated that factor 1 was negatively related to Co, Cr, Cu, Fe, Ni, and Pb while factor 2 was positively related to Cd, Hg, and Zn. Similar distribution of metals may be observed on isoline plots presented in Online Resource 4 for metal concentrations (mg kg^{-1}) measured in *S. uncinata* collected in Longyearbyen. Co, Cr, Cu, Fe, Ni, and Pb converge and form hotspots corresponding to the location of sites 6, 9–11, 17–19, 29, while Cd, Hg, and Zn converge and form hotspots corresponding to the location of sites 1–3 and sites 15, 20–21. It is difficult to explain the causes of distribution of this element in the examined bioindicators and, from a heuristic point of view, it is speculative. There are no data available concerning the element contents in emissions, concentration gradient analyses, isotopic ratio comparison, etc. These are all metals produced by transportation both by fuel exhausts and by abrasion in all types of vehicle parts (Kummer et al. 2009). However, coal mine residues as well as coal burning may be a significant source of Cd, Hg, and Zn (Askaer et al. 2008). For instance, elevated Hg levels of up to 1.5 mg kg^{-1} were found in coal waste deposited in the Nye Gruve I area. Ordination by PCCA calculated for 15 sites (Nos 53–67) of *S. uncinata* from the mine areas presented in Online Resource 5 shows that the first principal component discriminates mosses from sampling sites 53 and 54 (negative scores) situated on the slope of the abandoned Nye Gruve I mine. The second principal component discriminates *S. uncinata* from sites 62–64 (positive scores) also situated on the slope from the unnamed abandoned mine and *S. uncinata* from sites 57–59, 61 of

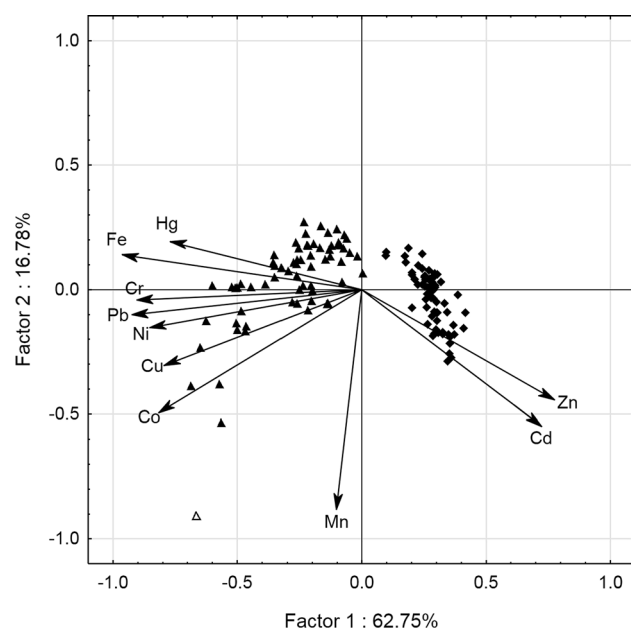


Fig. 2 Ordination plot based on the concentrations of Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, and Zn in *Sanionia uncinata* and *Salix polaris* leaves and projection of element concentrations on the component plane; full triangles *S. uncinata*, full diamonds *S. polaris*, empty triangle *S. uncinata* in site 10

the Nye Gruve II mine (negative scores). Projection of the variables on the factor plane indicated that *S. uncinata* collected from the Nye Gruve I mine was correlated with the highest concentrations of Co, Cr, Fe, Mn, Ni, and Pb in their tissues. *Sanionia uncinata* in sites 62–64 was correlated with the highest concentration of Cd and Zn. Mosses from sampling sites of the Nye Gruve II mine were positively correlated with the highest concentration of Hg in their tissues. Similar distribution of metals may be observed on isoline plots presented in Online Resource 5 for metal concentrations (mg kg^{-1}) measured in *S. uncinata* collected in these mine areas. Co, Cr, Fe, Mn, Ni, and Pb converge and form hotspots corresponding to the location of sites 53 and 54, while Cd and Zn converge and form hotspots corresponding to the location of sites 62–64 and mercury converges and forms hotspots corresponding to the location of sites 57–59, 61. Elevated levels of these metals in mosses collected on the slopes of the mines may be explained by the fact that Fe, Mn and Ni are the most abundant constituents of runoff from coal waste at Svalbard (Sřndergaard et al. 2007). Furthermore, various sulfide minerals in the waste material of pyrite ore may be the source of Cd, Pb, and Zn (Sřndergaard et al. 2007). The results are in agreement with Askaer et al. (2008) that many of such mine waste dumps are hazardous to the environment and need permanent investigation.

Conclusions

The present investigation reveals local pollution affecting metal levels in common plant species used as bioindicators in part of Spitsbergen. This type of study helps to understand the biogeochemical processes of human-induced contamination and to protect unique places in this part of the Arctic.

The willow *S. polaris* may be used in phytoaccumulation and therefore in the bioremediation and bioindication of Cd and Zn from its environment.

Stems of *S. polaris* from Longyearbyen are better bioindicators of Cr, Cu, Hg, Ni, and Pb and poorer bioindicators of Cd, Mn, and Zn than leaves of this species.

S. polaris (both stems and leaves) was a better bioindicator of Cd and Zn concentrations than green gametophytes of *S. uncinata*.

S. uncinata was a better bioindicator of Co, Cr, Cu, Fe, Hg, Mn, Ni, and Pb than *S. polaris*.

Acknowledgements This research was supported by the University of Wrocław (1072/S/KEBOS/2017). According to the Act of 15 June 2001 No. 79 relating to the Protection of the Environment in Svalbard (the Svalbard Environmental Protection Act) the scientific activity as described did not require special permission. We thank Andrzej Leszek Rudecki and Teresa Łysiak for their assistance with chemical analyses.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

Research involving human and animal rights This article does not contain any studies with human participants or animals performed by any of the authors.

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